

Gas Content and Star Formation Thresholds in the Evolution of Spiral Galaxies

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Abstract.

The gas mass fraction of spiral galaxies is strongly correlated with the central surface brightness of their disks. There exist many dim galaxies with long gas consumption time scales and $f_g > 0.5$. This resolves the gas consumption paradox.

The surface density of gas follows the optical surface brightness, but does not vary by as large a factor. This is the signature of a critical density threshold for star formation. Such a mechanism seems to be responsible for the slow evolution of dim galaxies.

GAS CONTENT

The fraction of baryonic mass which has been converted from gas into stars is a fundamental measure of the degree of evolution of a galaxy. The gas content of spiral galaxies is a strongly correlated with the optical surface brightness of their disks (Fig. 1). This must be an evolutionary effect indicative of the rate of galaxy evolution in disks of differing surface mass densities [1,2].

A complete analysis describing the details of the derivation of the gas mass fractions is given elsewhere [3]. Gas content increases strongly with decreasing surface brightness. An important consequence of this is the end of the gas consumption paradox. Gas rich galaxies do exist, and are quite common [4].

DISK EVOLUTION

The present epoch gas fraction is a direct chronometer of the star formation history. There is degeneracy in how a given f_g may be reached, but the evolutionary rate and/or age of spiral galaxies must vary systematically with surface brightness to give the observed correlation. Burst and fade scenarios

[5] can be completely ruled out as these should result in low not high f_g for dim galaxies. Indeed, it is difficult to have exponentially declining star formation histories in galaxies with $f_g > 0.5$ unless they are quite young. Such objects can be old if the star formation rate increases rather than decreases with time, but only at the expense of making the mean age of the stars very young (a few Gyr). A roughly constant star formation rate is more plausible, but requires an intermediate age (8 or 10 Gyr rather than 12 or 14 Gyr).

Galaxies with $f_g > 0.5$ have most of their star forming potential in the *future*. These gas rich galaxies are inevitably morphologically late types (Sd & Sm). They could not possibly have experienced an evolution of rapid gas consumption followed by rapid fading. Yet this is precisely the evolution inferred for late types from high redshift data [6]. These results are both sound and utterly contradictory. The nature of the faint blue galaxies therefore remains a mystery.

STAR FORMATION

Why have dim galaxies converted so little of their gas into stars?

A first approximation of the dependence of the star formation rate on gas density is the Schmidt Law:

$$\dot{f}_g \propto \Sigma_g^N. \quad (1)$$

Kennicutt [7] finds $N = 1.3 \pm 0.3$. By this criterion, low surface density disks should evolve slowly, but this alone is not adequate to explain the observations. Gas surface density does follow optical surface brightness, but does not vary by as large a factor [8]. Roughly speaking, Σ_g drops by a factor of 2 for a factor of 5 drop in μ_0 . Making the usual assumption that the amount of light traces the global star formation rate averaged over a Hubble time,

$$\frac{\Sigma_{opt}(HSB)/T_H}{\Sigma_{opt}(LSB)/T_H} \approx \frac{\dot{f}_g(HSB)}{\dot{f}_g(LSB)} = \left[\frac{\Sigma_g(HSB)}{\Sigma_g(LSB)} \right]^N \rightarrow 5 = 2^N \quad (2)$$

requires a value of $N \approx 2.3$, much larger than observed. Though this is a crude calculation, it is a conservative one: other plausible assumptions require even larger N .

The next order approximation for star formation is based on local gravitational stability in the disk [7]. This leads to a critical density threshold below which star formation is suppressed:

$$\Sigma_c = \frac{\sigma}{3.4G} \frac{V}{R} \left(1 + \frac{R}{V} \frac{dV}{dR} \right)^{1/2}. \quad (3)$$

This provides a good explanation for the evolutionary sluggishness of low surface brightness disks: they are at or below the critical threshold.

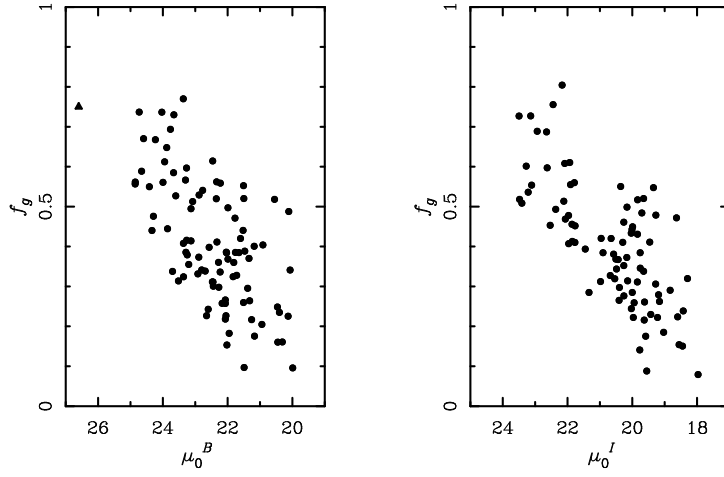


FIGURE 1. The gas mass fraction as a function of disk central surface brightness. The two panels show results derived independently from a) *B*-band and b) *I*-band data. These give consistent results. The slopes differ slightly because higher surface brightness galaxies tend to be redder. The data show a strong correlation [$\mathcal{R} = 0.63$ in (a)] with gas fraction decreasing as surface brightness increases. This goes in the sense expected if low densities inhibit star formation.

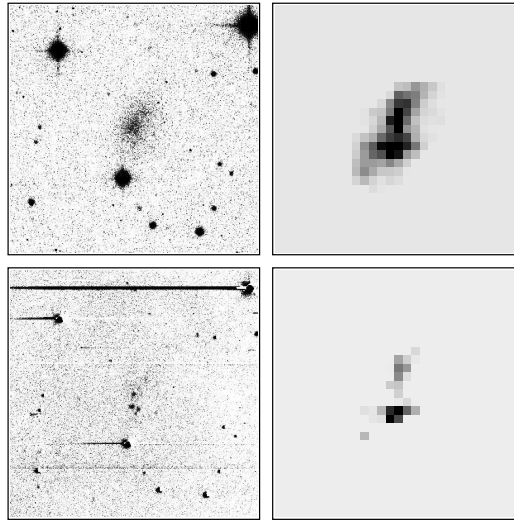


FIGURE 2. The low surface brightness galaxy F563-V1. a) Broad band optical (*V*-band) image. b) HI gas distribution. c) Continuum subtracted H α emission. d) Critical density map. The critical density map is constructed by dividing the gas distribution in (b) by Σ_c as given in the text. Only regions near to or exceeding this threshold are shown. There is a reasonable correspondence between these areas which should be forming stars and those which actually are in (c).

We have tested this in a radially averaged way [9] and it works well: lower surface brightness disks are generally further into the critical regime. We can also test this formulation on a point by point basis (Fig. 2). In many cases it works well, there being a reasonable coincidence between regions where $\Sigma_g > \Sigma_c$ and the location of HII regions.

Nevertheless, the agreement between prediction and observation is by no means perfect in all cases. The Σ_c criterion seems especially prone to failure in the solid-body portion of the slowly rising rotation curves of low surface brightness galaxies. This is perhaps not surprising; there is very little shear in these regions. Stability is maintained for lower Q values, and asymmetries can persist in the gas for many dynamical times. Nevertheless, star formation is sometimes observed in regions which should be stable. It seems that further physics is at work — both the Schmidt law and Kennicutt's critical density criteria are operative and directly relevant to the global evolution of galaxies, but they are not the end of the story.

Though further physics is required to understand all the details of star formation, one basic result is clear. Surface mass density is a critical parameter in determining the evolutionary rate of disks. Dim galaxies have consumed little of their gas because of their low surface densities.

GALAXY FORMATION

If surface density determines the evolution of disk galaxies, what determines the surface density? The origin of disk surface density is probably related to the amplitude of the density fluctuation from which a galaxy was born. Lesser density perturbations will expand longer before turn around, and collapse later. This results in a lower final mass concentration and a younger age, as observed. Density begets density.

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